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Many kinetic energy missiles are designed to penetrate through concrete targets before the initiation of reaction of energetic materials housed in the missile. Critical loading conditions for the design of such missiles are not the aerodynamic forces but the loading environment during penetration through concrete. At high striking velocities, in the range of 1200 - 1500 m/sec, sharp noses of steel projectiles are blunted and material is eroded from the nose of the projectile. Melted and refrozen steel are observed on the shank of the projectile. Sections of the steel projectiles, recovered following penetration tests through concrete have displayed heat affected zone, evidence of phase transformation to the gamma phase and melting. An undesirable effect of the nose erosion is the deviation of the trajectory through the concrete from the intended trajectory.

The objectives of the research program are to understand the mechanisms responsible for the nose erosion of kinetic energy projectiles during impact and penetration through different targets like concrete, soil and metal at high striking velocities in the range of 1200 - 1500 meter per second and use the understanding to design materials and structure of the kinetic energy projectiles

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Thermomechanics of Impact and Penetration

Submitted by

School of Aerospace Engineering
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PRINCIPAL INVESTIGATOR: SATHYA. H. HANAGUD

GEORGIA INSTITUTE OF TECHNOLOGY
Unit of the University System of Georgia
Atlanta, Georgia 30332

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THERMOMECHANICS OF IMPACT & PENETRATION

By

S. Hanagud, Georgia Tech, Atlanta, GA

1. Introduction

Many kinetic energy missiles are designed to penetrate through concrete targets before the initiation of reaction of energetic materials housed in the missile. Critical loading conditions for the design of such missiles are not the aerodynamic forces but the loading environment during penetration through concrete. At high striking velocities, in the range of 1200 – 1500 m/sec, sharp noses of steel projectiles are blunted and material is eroded from the nose of the projectile. Melted and refrozen steel are observed on the shank of the projectile. Sections of the steel projectiles, recovered following penetration tests through concrete have displayed heat affected zone, evidence of phase transformation to the gamma phase and melting. An undesirable effect of the nose erosion is the deviation of the trajectory through the concrete from the intended trajectory.

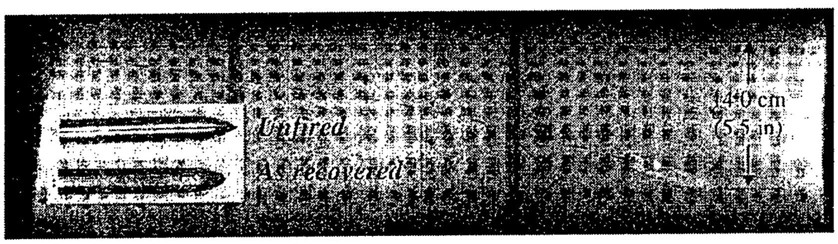

Figure 1. Steel projectiles before and after penetrations through concrete target.

2. Objectives

The objectives of the research program are to understand the mechanisms responsible for the nose erosion of kinetic energy projectiles during impact and penetration through different targets like concrete, soil and metal at high striking velocities in the range of 1200 to 1500 meter per second and use the understanding to design materials and structure of the kinetic energy projectiles to minimize the nose erosion, the resulting deviation of the trajectory of the projectile from the intended trajectory through the target, and other issues like the stability (buckling) of the projectile and failure of the projectile prior to completion of the mission.

3. Method of approach

The method of approach is as follows:

1. First task is to examine the mechanisms responsible the nose erosion of steel kinetic energy projectiles during impact and penetration through targets like concrete targets, at striking velocities in the range of 1200 to 1500 meters per second.

2. The second task is to formulate models that can support the mechanisms and can be used to simulate the penetration process and the nose erosion process. The models should include appropriate thermodynamics and continuum mechanics and should reflect the high strain rates associated with the impact and penetration event. The simulation results can be used to improve the hypothesized nose erosion mechanisms.
3. The next task is to design representative tests, conduct tests and develop any needed measurement techniques to determine parameters of the models and validate the effectiveness of the model.
4. Use the formulated models to examine the instability of the projectile during the penetration path, stress distribution in the projectile and the failure of the projectile prior to completion of the mission.

4. Innovations in science

In the past, impact and penetration problems have been studied extensively. However, the nose erosion problem, the change of the nose shape and the resulting deviation of the trajectory from the intended trajectory are new observations during the last decade. In addition to these observations, other important issues include the buckling of the projectile, failure of the projectile prior to completion of mission and an incorporation of multifunctional characteristics to the projectile to optimize the projectile for the size and energy released per unit weight. Currently, we do not have an understanding of the mechanisms that are responsible for the nose erosion, models that can simulate the penetration path with nose erosion or target resisting force with nose erosion, penetration failure, and instability or dynamic buckling of the projectile. The nose erosion is due to interaction of two different systems: metal projectile and the target. Such erosion problems are also observed in the nozzle erosion of solid rockets with two different systems consisting of nozzle and propellant decomposition products. Specific innovations in science are as follows.

- Non-equilibrium thermodynamic constitutive model are formulated to describe plasticity and phase transition at high strain rates. The development of the models is in the framework of continuum mechanics with large or finite deformations. In the first phase of the project, a dislocation-based plasticity model is formulated to account for the heating of the projectile during the impact and penetration events.

- The development uses a mixture theory and a combination of internal variables and extended non-equilibrium state variables in formulating the models. Appropriate evolution equations are formulated for various fluxes associated with dislocation motion, viscous stresses and heat. The formulated equations are subjected to the constraints of the second law of thermodynamics and the principle of material frame indifference.

5. Innovations in design

Basic research contributions to innovations in design include development of techniques to design the structure and materials of a kinetic energy projectile to minimize or eliminate the nose erosion, eliminate projectile failure, buckling of the projectile and any trajectory deviation from the intended trajectory. These projectiles penetrate through targets like concrete, soil and rock before they detonate. We are collaborating with scientists and engineers from AFRL/MN at

Eglin Air Force Base in formulating the basic research program that will result in contributions that can be used in practical designs.

6. Research progress

6.1 Mechanism of penetration at nose erosion

Following the impact of the projectile into the target, an elastic forerunner and a shock wave are generated in the target. Similarly, an elastic wave and shock wave propagate in the projectile. Very high stresses are generated near the ogival nose tip of the projectile. This results in plastic flow and the resulting plastic work in addition to the hydrostatic stresses. The plastic work results in a heating of the projectile that can cause phase transition including melting. However, the plasticity models that are currently used in the field of shock wave analysis of solids do not result in high temperatures and associated stresses that can cause phase transition. Thus, it is necessary to investigate and modify the models.

Several studies[1,2] have pointed out that a large number of dislocations are produced behind a shock wave and this is followed by a sudden release of dislocations that can result in conditions of high temperature and the associated pressures (stresses) that are favorable for phase transition. Then our first attempt is to formulate a model that can accommodate these phenomena.

Most of these changes, including the production of dislocations and heating are taking place behind the shock front. Thus, we may not be able to assume that "thermodynamic equilibrium" exists. This thermodynamic equilibrium assumption is usually made at a shock front where it is assumed that thermodynamic equilibrium exits in front of the shock wave and behind the wave. Thus, it is implicitly assumed all nonequilibrium thermodynamic effects take place in a thin surface that represents shock discontinuity or a shock wave. In the case of the impact of the ogival nose of a projectile into a target these phase changes, including melting are taking place over a wide region and heating the projectile material with a time delay. It is not justifiable to assume that we have a "phase transition discontinuity front". Thus, a non-equilibrium thermodynamic model for plasticity is developed.

6.2 Nonequilibrium thermodynamic model for plastic work

Our model combines the use of internal variables and extended nonequilibrium state variables or thermodynamic fluxes. The objective is to formulate a model to describe the dynamic behavior of metals under high strain rates. The two fields, i.e. mechanical and thermal fields, are involved in our model. They are coupled with each other through mechanical and thermal processes. For each process, the corresponding thermodynamic fluxes, as extended nonequilibrium state variables are introduced. For mechanical viscous process and heat transport process, nonequilibrium stresses and heat flux are the corresponding fluxes. Since each element may consist of multiple phase components, the volume fractions of each phase are chosen to be

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[1] Meyers, M. A., Dynamic behavior of material, Jon Wiley & Sons, Inc, 1994.

[2] Armstrong, R. W., and Zerilli, F. J., "Dislocation mechanics aspects of plastic instability and shear banding," Mechanics of Materials, v. 17, 1994, pp. 319-327.

internal variables. A mixture theory is used to include multiple phase. The nucleation flux for each phase component of mixture theory is the corresponding thermodynamic flux. The second set of internal variables is to depict the micro-defect dislocation in the element. The dislocation density, a second order tensor, is the internal variable to describe each slip system. The dislocation motion as another second order tensor is the corresponding thermodynamic flux or extended state variable. In summary, at any instant, each element can be at its local nonequilibrium state. The local nonequilibrium state can be specified by classical state variables (local equilibrium state variables) and extended state variables (local nonequilibrium state variables). Extended state variables, thermodynamic fluxes, are to describe the local nonequilibrium fluctuations. The state functions like internal energy, free energy and entropy are assumed to exist and are functions of all the independent state variables. The second law of thermodynamics and the principle of material frame indifference are enforced in the constitutive relations.

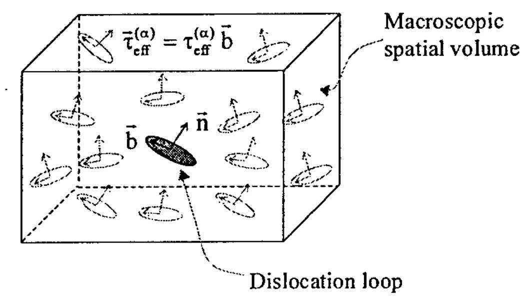

Figure 2. Dislocation network in a differential volume.

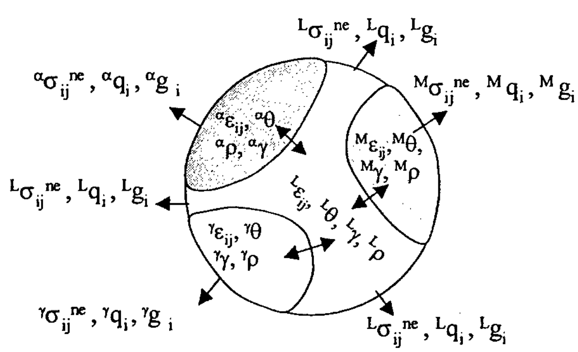

Figure 3. Mixture theory and phase components.

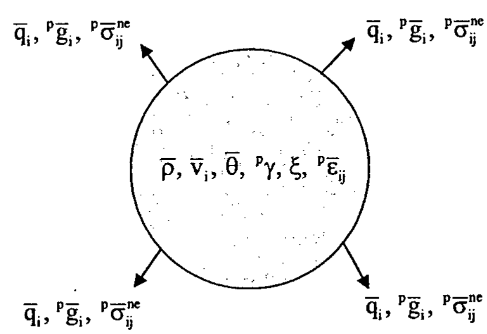

Figure 4. A smearing technique in mixture theory.

First, a deterministic dislocation based plasticity model is formulated to delineate the evolution of dislocation network and the associated bulk plastic behavior. This formulation can be later modified to include a probabilistic model. This approach is based on the description of every discrete slip system. A simply-connected-boundary-based mixture theory is developed for the generalized continuum, in the Eulerian description. The complete formulation is compatible with the principle of material frame indifference and the second law of thermodynamics. The summary of equations is as follows.

Constitutive Relations for Mixture

It is assumed that the stress tensor can be separated into a pressure term which is governed by the equation of state and a stress deviator.

(a) *The rate form of the equation of state*

$$\dot{\overline{P}}^e = A(\overline{\rho},\overline{\theta})\left(\frac{1}{3}\overline{V}_{ii}^e\right) + B(\overline{\rho},\overline{\theta})\dot{\overline{\theta}}$$

which is obtained from the equation of state $\overline{P}^e = \overline{P}^e(\overline{\rho}, \overline{\theta})$.

(b) *The rate form of the deviatoritic relation*

$$\overset{\circ}{\overline{\sigma}}{}_{ij}^{e\,\prime} = \overline{G}_{ijkl}\overline{V}_{kl}^{e\,\prime}$$

(c) *Evolution of Dislocations*

$$\frac{D\rho_d^{(\alpha)}}{Dt} + \rho_d^{(\alpha)}\frac{\partial \overline{v}_k}{\partial x_k} = K^{(\alpha)}$$

The term on the right-hand side is the source term $K^{(\alpha)}$. The source contains the contributions due to dislocation multiplication $K_m^{(\alpha)}$,dislocation nucleation $K_n^{(\alpha)}$ behind the shock front, and dislocation reaction $K_J^{(\alpha)}$.

$$K^{(\alpha)} = K_m^{(\alpha)} + K_n^{(\alpha)} + K_J^{(\alpha)}$$

The Frank-Reed model for dislocation multiplication, which is based on dislocation loops formed by pinned dislocations, is

$$K_m^{(\alpha)} = \frac{\chi_L^{(\alpha)}(\theta)}{E_L}\rho_d^{(\alpha)}b^{(\alpha)}v^{(\alpha)}\tau_{eff}^{(\alpha)}$$

Where E_L is the average dislocation line energy over all slip systems. $\chi_L^{(\alpha)}$ is the fraction of the average plastic work that contributes to the formation of dislocation segments (α). $\chi_L^{(\alpha)}$ depends on temperature θ.

At the shock fronts, a lattice interface is generated by the sharp gradient of the deformation rate. This interface becomes a bed for dislocation nucleation. A lattice mismatched interface is generated and of high elastic strain energy. As the shock becomes stronger, this high elastic strain energy becomes larger than some critical energy level. Then a large number of misfit dislocation nucleation nucleates at this interface[1]. The rate of this dislocation nucleation at the shock front is assumed to be proportional to the rate of the stored elastic strain energy. The shock front is indicated by a sharp stress gradient. Then,

$$K_n^{(\alpha)} = \begin{cases} \dfrac{\chi_D^{(\alpha)}}{E_L} f(\overline{\sigma}_{ij}^e) & f(\overline{\sigma}_{ij}^e) > f_{cr} \text{ and at shock front} \\ 0 & \text{otherwise} \end{cases}$$

where $\chi_D^{(\alpha)}$ is the fraction of the average stored interface energy that contributes to the formation of dislocation segments (α). $f(\overline{\sigma}_{ij}^e) = \overline{\sigma}_{ij}^e \overline{V}_{ij}^e$ is the rate of specific volume elastic strain energy at the shock front. For shock analysis, $f(\overline{\sigma}_{ij}^e) = \frac{1}{3}\overline{P}^e \overline{V}_{ii}^e$, where $\overline{P}^e$ is the hydrostatic pressure.

The reaction between dislocation segments of two different slip systems may lead to the formation of a junction segment of a new slip system with a new Burgers vector. At the same time, the motion of dislocation segments may break the existing junctions. Therefore, the loss rate of dislocation segments in slip system (α), $K_{J-}^{(\alpha)}$, due to their reaction with dislocation segments of slip system (β), is written as follows.

$$K_{J-}^{(\alpha)} = -\frac{1}{\sqrt{\rho_d}} \sum_{\beta} \left[R_F^{(\alpha)(\beta)} (v^{(\alpha)} + v^{(\beta)}) + R_B^{(\alpha)(\beta)} v^{(\beta)} \right] \rho_d^{(\alpha)} \rho_d^{(\beta)}$$

Where $R_F^{(\alpha)(\beta)}$ is the probability that two dislocation segments of slip system (α) and (β) react and form a new slip system, while $R_B^{(\alpha)(\beta)}$ is the probability for a dislocation segment on slip system (β) to break a junction of slip system (α). ρ_d is the average dislocation density in a infinitesimal volume, which is,

$$\rho_d = \sum_{\alpha} \rho_d^{(\alpha)}$$

The rate of dislocation formation for the slip system (α), $K_{J+}^{(\alpha)}$, caused by junction formation and breaking, is given by

$$K_{J+}^{(\alpha)} = \frac{1}{\sqrt{\rho_d}} \sum_{\beta 2} \sum_{\beta 1} R_c^{(\alpha)(\beta 1)(\beta 2)} v^{(\beta 1)} v^{(\beta 2)} \rho_d^{(\beta 1)} \rho_d^{(\beta 2)}$$

Where $R_c^{(\alpha)(\beta 1)(\beta 2)}$ is the construction probability of dislocation segments of slip system (α) due to the reaction between dislocation segments of slip systems $(\beta 1)$ and $(\beta 2)$. The non-dimensional quantities $R_F^{(\alpha)(\beta)}$, $R_B^{(\alpha)(\beta)}$ and $R_c^{(\alpha)(\beta 1)(\beta 2)}$ are material parameters. They have to be obtained by measurement or computer simulation of junction processes. The rate of change of the dislocation segments of slip system (α) is written as

$$K_J^{(\alpha)} = -K_{J-}^{(\alpha)} + K_{J+}^{(\alpha)}$$

(d) *Evolution of non-equilibrium stresses*

$$\bar{\tau}_\sigma\,(\overset{\circ}{\bar{\sigma}}{}^{ne}_{ij}) = -\bar{\sigma}^{ne}_{ij} + \bar{\eta}_{ijkl}\bar{V}^{e}_{kl}$$

where the mixture viscosity coefficients and the mixture viscous relaxation time are

$$\bar{\eta}_{ijkl} = \left(\sum_p {}^p\xi({}^p\eta_{ijkl})^{-1}\right)^{-1};\quad \bar{\tau}_\sigma = \bar{\eta}_{ijkl}\sum_p {}^p\xi\ {}^p\tau_\sigma({}^p\eta_{ijkl})^{-1}$$

(e) *Evolution of heat flux*

$$\bar{\tau}_q\,\overset{\circ}{\bar{\bar{q}}}_i = -\bar{\bar{q}}_i - \bar{k}_{ij}\frac{\partial\bar{\theta}}{\partial x_j}$$

where the mixture thermal conduction coefficients and the mixture thermal diffusion relaxation time are

$$\bar{k}_{ij} = \sum_p {}^p\xi\ {}^pk_{ij};\quad \bar{\tau}_q \approx {}^p\tau_q$$

(f) *Evolution of nucleation fluxes*

$${}^p\tau_g\,({}^p\overset{\circ}{\bar{g}}_i) = -{}^p\bar{g}_i - \sum_m\left({}^{pm}\kappa_{ij}\frac{\partial(\bar{\rho}^m\gamma)}{\partial x_j}\right)$$

where ${}^{pm}\kappa_{ij}$ are the coefficients of mass diffusion of phase p due to the mass concentration gradient of phase m. Some properties of ${}^{pm}\kappa_{ij}$ are considered. Let consider the corresponding CIT model in the limit of ${}^p\tau_g = 0$. From the Onsager's reciprocal principle, the interaction between mass diffusion of any two phase components is reciprocal. This means that the coefficients ${}^{pm}\kappa_{ij}$ have symmetric properties with respect to the upper index. That is,

$${}^{pm}\kappa_{ij} = {}^{mp}\kappa_{ij}$$

(g) *Evolution of dislocation motion*

The motion of the slip system (α) is driven by the local resolved shear stress $\tau_{eff}^{(\alpha)}$. It comprises of three parts: the external (long range) shear stress resolved on the slip system (α), $\tau_{ext}^{(\alpha)}$, the internal shear stress due to the morphological configuration of dislocation segments such as dislocation self-interactions and short-range interaction with the obstacles, $\tau_{int}^{(\alpha)}$, and the intrinsic lattice resistance including temperature-dependent Pierels resistance $\tau_{fri}^{(\alpha)}(\theta)$ and electron and phonon drag, $\tau_{drag}^{(\alpha)}(\theta)$. That is,

$$\tau^{(\alpha)}_{eff} = \tau^{(\alpha)}_{ext} - \tau^{(\alpha)}_{int} - \tau^{(\alpha)}_{drag} - \tau^{(\alpha)}_{fri}$$

The extenal resolved shear stress is related to the macroscopic stress tensor by the Peach-Koehler formula,

$$\tau_{ext}^{(\alpha)} = \overline{\sigma}_{ij} Z_{ij}^{(\alpha)}$$

The internal stress may be decribed by a line tension approximation. That is,

$$\tau_{int}^{(\alpha)} = \frac{\varsigma^{(\alpha)} \overline{G} b^{(\alpha)}}{\Delta L}$$

where $\varsigma^{(\alpha)}$ is the non-dimensional effective coefficient, $\overline{G}$ the average shear modulus of the crystal, $b^{(\alpha)}$ the magnitde of Burgers vector, and ΔL the avearged distance between two closest dislocation segments. Obviously, ΔL decreases as the average dislocation density ρ_d increases. It is assumed that

$$\Delta L = \frac{1}{\sqrt{\rho_d}}$$

The drag mechanisms on the dislocation motions are due to the relaxation effects during the interaction of the dislocation with phonons and with electrons; also due to the relaxation effects in the dislocation core. For metals at high temperature, phonon drag is the dominant drag mechanism; at low temperature, electron drag is the major mechanism. To a first approximation, a Newtonian viscous model is used for these drag effects. That is,

$$\tau_{drag}^{(\alpha)} = B^{(\alpha)} v^{(\alpha)}$$

where $B^{(\alpha)}$ is the viscous coeffcitent, which can be a function of the dislocation motion. For bcc cystals, other drag laws may apply.

$$\begin{cases} \tau_d^{(\alpha)} \dfrac{Dv^{(\alpha)}}{Dt} = -v^{(\alpha)} + \dfrac{1}{k_d^{(\alpha)}(\theta)} \tau_{eff}^{(\alpha)} & \text{if } \tau_{ext}^{(\alpha)} > \tau_{ext,c} \\ v^{(\alpha)} = 0 & \text{otherwise} \end{cases}$$

where $\tau_d^{(\alpha)}$ is the relaxation time of dislocation motion. This relaxation of dislocation motion correlates to the relaxation of drag effects. Therefore, $\tau_d^{(\alpha)}$ depends on the relaxation time of the dominant drag effects. For metals, The order of $\tau_d^{(\alpha)}$ is comparable to the characteristic time scales of the high-rate dynamic processes such as the shock wave traveling through the dislocation network in a infinitesimal volume. The coefficient $k_d^{(\alpha)}$ is the resistance to the dislocation motion, which decreases with increase in temperature and represents a thermal softening effect, e.g., a model similar to the Johnson-Cook model is employed.

$$k_d^{(\alpha)}(\theta) = k_d^{(\alpha)}(\theta_0)\left(1 + \alpha_d \frac{\Delta\theta}{\theta_0}\right)^{-1}$$

where α_d is the non-dimensional thermal softening coefficient, and θ_0 the reference temperature. The critical stress $\tau_{ext,c}$ depends on the average dislocation density ρ_d, which agrees with the strain rate hardening effects that are caused by dislocation pile-ups, and also depends on the temperature. A phenomenological formulation of $\tau_{ext,c}$ is given by

$$\tau_{ext,c} = \tau_{ext,c0} + \tau_{cp}\sqrt{\frac{\rho_d}{\rho_{d0}} - 1} + \tau_{c\theta}\left(\frac{\theta}{\theta_0} - 1\right)$$

where the sub index "0" indicates the reference state. Here, $\tau_{c\theta}$ and τ_{cp} are constant reference stresses. As dislocations pile-up, the slip system changes to a denser configuration and therefore the mobility of the slip system reduces, in other words, the critical stress increases. However, at the early stage of dislocation "pile-up", this hardening effect is not obvious and can be assumed to be negligible. Only up to some level of dislocation "pile-up", denoted by some threshold value $\rho_{d\text{-}HP}$, the hardening is counted. In mathematical terms,

$$\tau_{cp} = \begin{cases} 0 & \rho_d < \rho_{d-HP} \\ \tau_{cp0} & \rho_d \geq \rho_{d-HP} \end{cases}$$

For dislocation based plasticity, it is seen that a time history dependent stress-strain relation is not needed. Since at each instant, either before, during or after plastic deformation, the state can be distinguished by the different dislocation distribution. The future state is totally determined by the current state. The applicablity of dislocation based plasticity depends on the possibility of obtaining the initial dislocation data. It is realized that this could be done by spectroscopic or electroscopic studies of the specimen. However, the current techniques to conduct dislocation measurements and quantitively decribe the constitutive relations, are limited and time consuming.

Entropy Evolution and second law of thermodynamics

Preliminary work has been completed on the entropy evolution equation, clarify the satisfaction of the second law of thermodynamics and the material frame indifference.

7. Supported graduate students

(1) Abhijit Gogulapati, MS, graduating at May 2004.

(2) Vindhya Narayanan, MS, graduating at May 2004, and is continuing the work toward Ph.D.

Papers presented and to be published

1. X. Lu, and S. Hanagud, "Thermomechanics of impact and penetration of metallic projectile into concretes: Formation of shear bands," IMECE2003-42793, 2003 ASME Internal Mechanical Engineering Congress, Nov. 15 – 21, Washington, D.C..
2. X. Lu and S. Hanagud, "Phase Transitions and Dislocation-Based Plasticity at High-Strain-Rates in Solids", 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference AIAA-2004-1920.

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